Naval Research Laboratory
Washington, DC 20375-5320

NRL/MR/7123--98-8199

Coherent Acoustic Communications During the Littoral Warfare Advanced Development 98-1 and SCV-97 Experiments

A. Al-Kurd
J. Schindall
T.C. Yang
E. Carey

Acoustic Signal Processing Branch
Acoustics Division

September 30, 1998

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave Blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 30, 1998	Memorandum

4. TITLE AND SUBTITLE

Coherent Acoustic Communications During the Littoral Warfare Advanced Development 98-1 and SCV-97 Experiments

5. FUNDING NUMBERS

6. AUTHOR(S)

A. Al-Kurd, J. Schindall, T.C. Yang, and E. Carey

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory
Washington, DC 20375-5320

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/MR/7123--98-8199

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
Code 32
Arlington, VA 22217-5660

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

Coherent acoustic communication experiments were performed during two Littoral Warfare Advanced Development (LWAD) exercises. The first exercise, the 1997 System Concept Validation (SCV-97), was conducted September 1997 off the South Carolina coast. The second exercise (LWAD 98-1) was conducted in the Gulf of Mexico, 30 nmi south of Key West Florida. The Acoustic Communication (ACOMM) experiment during the SCV-97 was allotted Event 5 which included two segments, one hour each. The ACOMM waveforms were projected using a mid-frequency acoustic source (BSDS) and received at multiple platforms using sonar system AN/SQS-53C, Vertical arrays (VLA), sonobuoys (SSQ-57A), and a submerged acoustic receiver. The received signals were stored on DAT and Exabyte tapes for post experiment processing. During LWAD 98-1 the ACOMM signals were projected using a mid-frequency acoustic source (F-56). The signals were received at multiple platforms using VLA's and sonobuoys. Two receiving platforms had ACOMM modems on board, one modem was a dedicated receiver and real-time signal processor, the other modem was an alternate receiver and transmitter. When the F56 was idle, the second modem would transmit mid-frequency or high frequency ACOMM signals. The received signals were processed in situ and stored on DAT tapes for post experiment analysis. The analysis of the SCV-97 and LWAD 98-1 experiments data show significant time-spread and a very strong multipath acoustic propagation environment.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Underwater Acoustics	27
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102

Coherent Acoustic Communications During the Littoral Warfare Advanced Development 98-1 and SCV-97 Experiments

A. Al-Kurd, J. Schindall, T. C. Yang, and E. Carey

Naval Research Laboratory

Washington, DC 20375

Abstract

Coherent acoustic communication experiments were performed during two Littoral Warfare Advanced Development (LWAD) exercises. The first exercise, the 1997 System Concept Validation (SCV-97), was conducted September 1997 off the South Carolina coast. The second exercise (LWAD 98-1) was conducted in the Gulf of Mexico, 30 nmi south of Key West Florida. The Acoustic Communication (ACOMM) experiment during the SCV-97 was allotted Event 5 which included two segments, one hour each. The ACOMM waveforms were projected using a mid-frequency acoustic source (BSDS) and received at multiple platforms using sonar system AN/SQS-53C, Vertical arrays (VLA), sonobouys (SSQ-57A), and a submerged acoustic receiver. The received signals were stored on DAT and Exabyte tapes for post experiment processing. During LWAD 98-1 the ACOMM signals were projected using a mid-frequency acoustic source (F-56). The signals were received at multiple platforms using VLA's and sonobuoys. Two receiving platforms had ACOMM modems on board, one modem was a dedicated receiver and real-time signal processor, the other modem was an alternate receiver and transmitter. When the F56 was idle, the second modem would transmit mid-frequency or high frequency ACOMM signals. The received signals were processed *in situ* and stored on DAT tapes for post experiment analysis. The analysis of the SCV-97 and LWAD 98-1 experiments data show significant time-spread and a very strong multipath acoustic propagation environment.

I. INTRODUCTION

The Littoral Warfare Advanced Development (LWAD) program, sponsored by the Office of Naval Research, provides cost-effective, at-sea, proof-of-concept experiments for littoral undersea warfare science and technology projects that have high potential for near-term transition to Fleet systems.

The complexity of underwater communications stems from the complexity of the oceanic environment. The ocean represents a band-limited and rapidly fading communication channel in

Manuscript approved August 10, 1998.

which the multipath structure is temporally unstable due to random fluctuations. Coherent data transmission using quadrature phase shift keying (QPSK) allows for efficient use of the available bandwidth.

Acoustic communications (ACOMM) experiments were conducted during two recent LWAD exercises. The main goals of the ACOMM experiments were to test the performance of the coherent communications method in the littoral environment, including real-time (*in situ)* processing of the received data using SHARC DSPs and post-experiment processing of the ACOMM signals at multiple platforms.

During the SCV-97, the ACOMM waveforms were projected using a mid-frequency drifting acoustic source and received on multiple platforms; some of them were drifting and others were moving. The first hour of event 5 (ACOMM segment 1) was conducted using 1000 b/s QPSK modulated waveforms. This part was performed at 0700 zulu on JD 257. The second hour of Event 5 (ACOMM segment 2) was conducted using 1500 b/s QPSK modulated waveforms. This part was performed at 2300 zulu on JD 258. During the first segment, the signals were received by AN/SQS 53C (DD Nicholson), by six drifting sonobouys, by a drifting VLA on the R/V Gosport, and by a submerged moving receiver (target). During the second segment the received signals were recorded only on the AN/SQS 53C.

During the LWAD 98-1 exercise, the ACOMM was allotted Event 6 which started on JD 342 at 2100 zulu and ended on JD 343 at 1200 zulu. The ACOMM waveforms were projected by a mid-frequency acoustic source towed by the R/V NAWC-LCU or by a drifting mid and high frequency source controlled by the acoustic modem on board the R/V NAWC 03. The ACOMM waveforms were QPSK modulated with baud rates of 1000, 1500, and 2000 b/s for mid-frequency transmission and baud rates of 6000 b/s, 10000 b/s, and 15000 b/s for high frequency transmission. The signals projected by the towed source were received and recorded at the other two platforms using VLA's. The VLA on board the R/V NAWC 38 platform was a dedicated receiver-processor (real-time *in situ* processing). The VLA on board the R/V NAWC 03 was an alternate receiver when the modem was not transmitting (there was no attempt to perform real-time processing on this modem); the received signals were recorded on DAT tapes for post experiment analysis.

During the experiment the modem triggered and started processing the received data at the selected baud rate whenever there was sufficient signal-to-noise ratio (SNR). The results of the real-time processing were saved to files. The starting point of a detected data packet and an indicator of the MSE were displayed. This information gave indication about the quality of the received signals and the performance of the receiver, but it was not sufficient for the operator to make substantial changes to the modem parameters at-sea.

Post-experiment analysis of both the SCV-97 and LWAD 98-1 experiments data show significant time-spread and a very strong multipath acoustic propagation environment. These results point

out many issues that remain to be researched.

II. Experiment Sites, Assets and Environmental Data

A. SCV-97 Experiment

The SCV-97 experiment was conducted off the Southern Carolina coast in the Long Bay area from September 6 to September 15, 1997. The ACOMM part of the experiment (Event 5) took place on September 14 from 0700 to 0800 zulu and on September 15 from 2300 to 2340 zulu. The experiment is described in detail in the SCV-97 Test Plan [1] and the SCV-97 Quick Look Proceedings [2]. The experiment site is shown in Fig. 1. The ocean bottom at this site consisted primarily of exposed limestone. Detailed geo-acoustic and oceanographic properties of the area are described in previous LWAD reports [2, 3, 4, 5].This area also was the site of the second LWAD Focused Technology Experiment (FTE 96-2) performed in August 1996.

Four platforms were involved in the SCV-97 ACOMM experiment: The R/V Acoustic Pioneer was the designated source ship; the R/V Gosport with a 16 element VLA was a designated receiver; the USS Nicholson (DD 982) with AN/SQS 53-C was a designated receiver. The signal was also received by a maneuvering submerged platform (henceforth denoted as a target). During the first segment of Event 5, all receiving platforms were in place and recorded the received ACOMM signals. During the second segment of Event 5, the R/V Gosport had left the operation area (OPERA), the ACOMM signals were recorded only on the AN/SQS 53-C. The distribution of the various assets during the first and second segments of the ACOMM experiment is illustrated in Figs. 2 and 3. The USS Nicholson and the target moved at approximate speeds of 11 and 6 knots, respectively; the Acoustic Pioneer and the Gosport were drifting.

The water column in the OPAREA was approximately 208 meters in depth. The VLA from the R/V Gosport was deployed to 65 meters. The BSDS source on the R/V Acoustic Pioneer was deployed to 60 meters. The separation between the R/V Acoustic Pioneer and the R/V Gosport was approximately 5.5 km. The range between the R/V Acoustic Pioneer and both the DD and the target varied, recall Figs. 2 and 3. During the first segment of the ACOMM experiment, the sea surface was relatively calm; wind speed as measured at the R/V Gosport fluctuated between 1 and 2 m/s. It is worth noting that the experiment was conducted near the Gulf Stream and this might affect the propagation and phase fluctuation of the acoustic signal. Figure 4 shows a typical sound-speed-profile (SSP) during the SCV-97 ACOMM experiment. During the ACOMM experiment the AN/SQS 53-C was operating in the 5F mode.

In the 5F mode, the SQS 53C forms 24 beams in the horizontal with an angle of 5^{o} between neighboring beams; the width in the vertical is 20^{o}. The SQS 53C operates in transmission and reception modes alternatively, it listens (receives) for 25 seconds then switches to transmission (in this case 1 to 1.5 seconds), this mode of operation led to a non-continuous reception. The received data has a gap every 25 seconds. The specification of the 5F mode are given in Table 1.

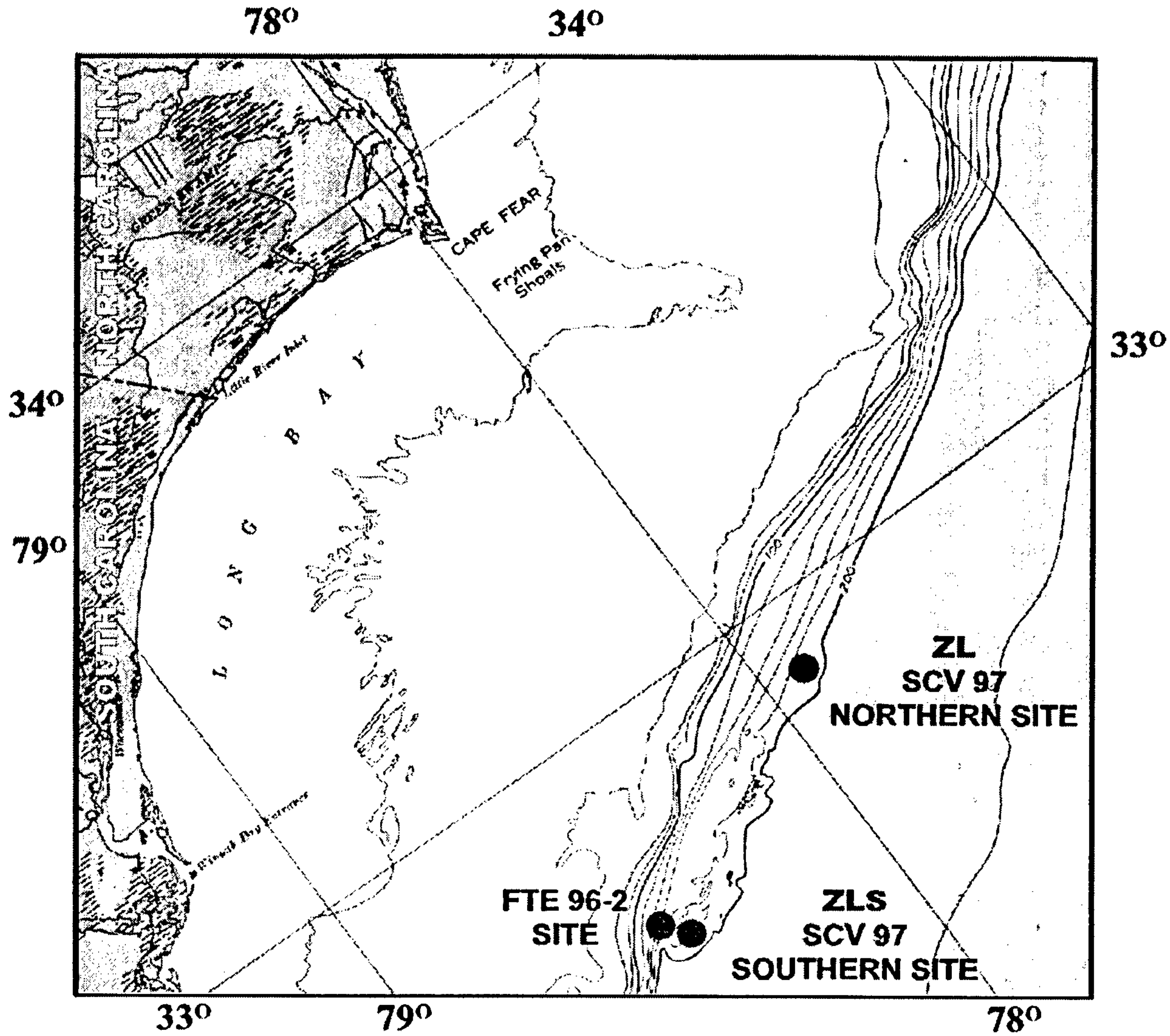


Figure 1: The experiment site for the LWAD SCV-97.

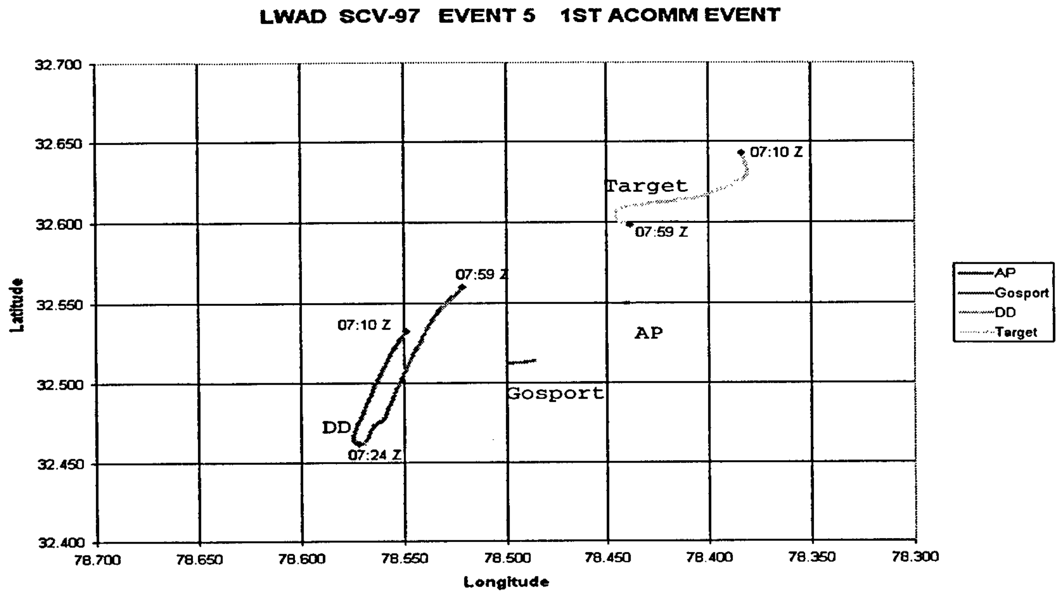


Figure 2: The distribution of the various assets during the 1st segment of the ACOMM experiment during the LWAD SCV-97.

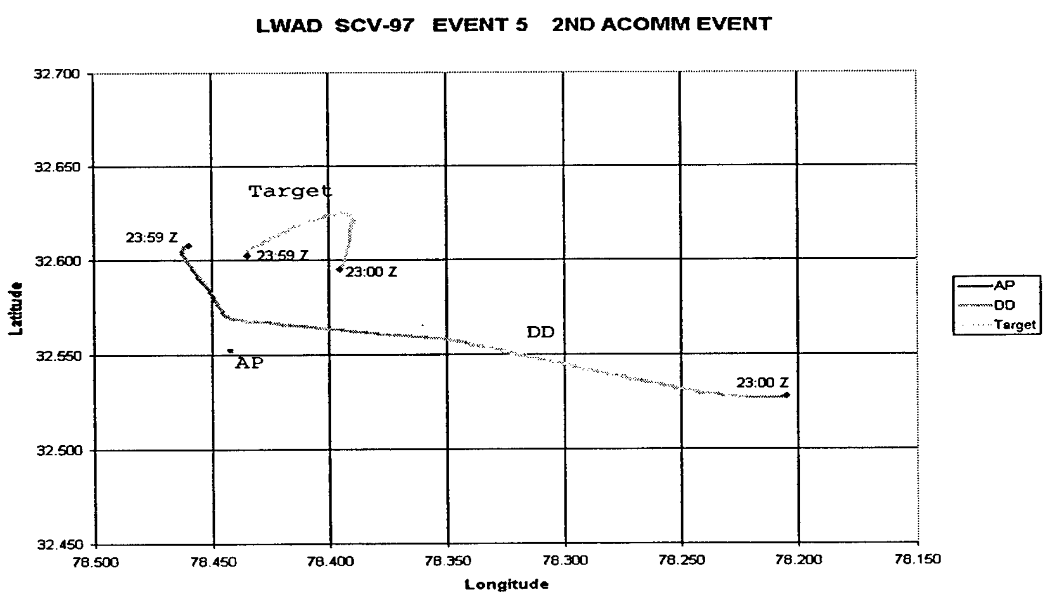


Figure 3: The distribution of the various assets during the 2nd segment of the ACOMM experiment during the LWAD SCV-97.

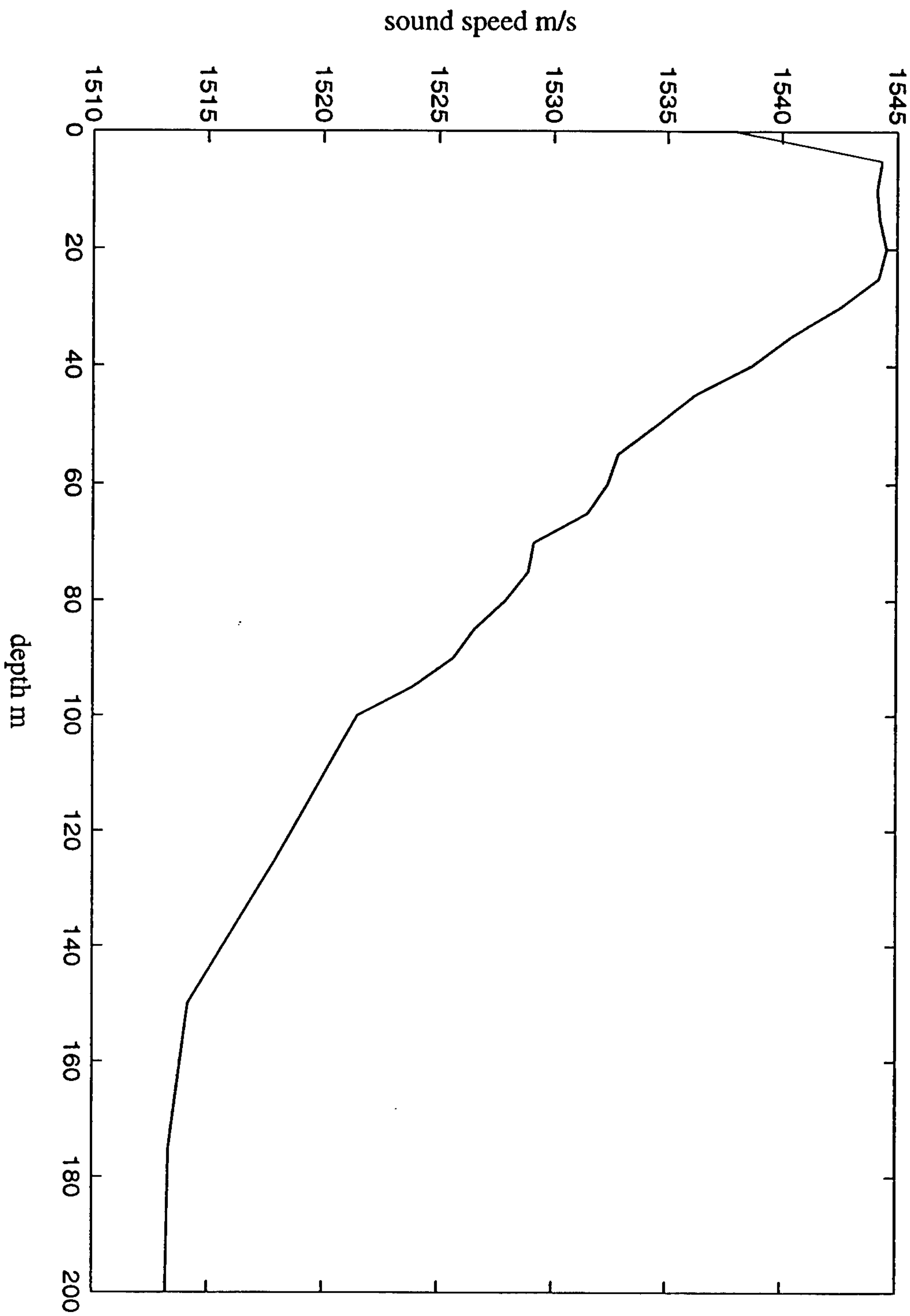


Figure 4: A representative sound speed profile during the LWAD SCV-97, CTD taken on board the Gosport.

Table 1: Parameters of the SQS 53C during the SCV-97 ACOMM experiment

parameter	value	explanation
trkbearing	0	track bearing (deg)
timeday	2.7701e+04	time (sec), last sys stat
tbearingr1	352.5073	true bearing of beam1
speed	11	speed of ship (knots)
soundpath	1	direct path
soundspeed	5067	sound speed (ft/s)
msgid	39	message i.d (5F)
fsample	2560	data sample rate (Hz)
fband	12	freq. band # (F1/F2/ZZF3/F4/F5)
deangle	2.9993	depression angle (deg) positive for down
date	19970914	TX date
cpupdown	0	upward freq. slide
course	21.6431	course of ship (deg)
botdepth	624	bottom depth (ft)

B. LWAD 98-1 Experiment

The LWAD 98-1 experiment took place 5-9 December 1998 in the Gulf of Mexico, approximately 34 nmi southwest of Key West. The ACOMM part of the experiment (Event 6) was planned to take place on the 7th of December 0900 to 2230 zulu, but was postponed due to adverse weather conditions. The ACOMM experiment started December 8th at 20:15 local time (0015 zulu) and ended December 9th at 08:04 local time (1204 zulu). The experiment is described in detail in the LWAD 98-1 Experiment Test Plan [6] and the LWAD 98-1 Quick Look Proceedings [7]. The experiment site is shown in Fig. 5. The ocean bottom at this site is hard and nearly absent of sediment. During most of the LWAD 98-1 experiment the Sea State was 3 to 4, except during the ACOMM segment in which the Sea State was estimated at 2.

Three platforms were involved in the ACOMM exercise: the R/V NAWC 38, the R/V NAWC 03, and the R/V LCU 1647. The R/V LCU 1647 was a dedicated source ship with a towed acoustic source (F56). The R/V NAWC 38 was a dedicated receiver and signal processing ship. The

NAWC 38 had the following gear on board: an acoustic modem for real-time *in situ* processing, data acquisition and recording systems, and a 16 element dual aperture VLA (eight phones were cut for high frequency, 20 kHz, and eight phones were cut for mid-frequency 3.5 kHz,). The R/V NAWC 03 was a receiver and an alternate source ship. The NAWC 03 had a 16 element VLA identical to that on the NAWC 38, a mid-frequency recording system, high and mid-frequency acoustic sources, and an acoustic modem used for triggering and controlling the acoustic source. The NAWC 03 was in the reception mode when the F56 source on the LCU was active; it was in the transmission mode when the F56 source was quiet. All ranges were referenced to the NAWC 38. The NAWC 38 and the NAWC 03 were drifting platforms while the LCU was a moving platform.

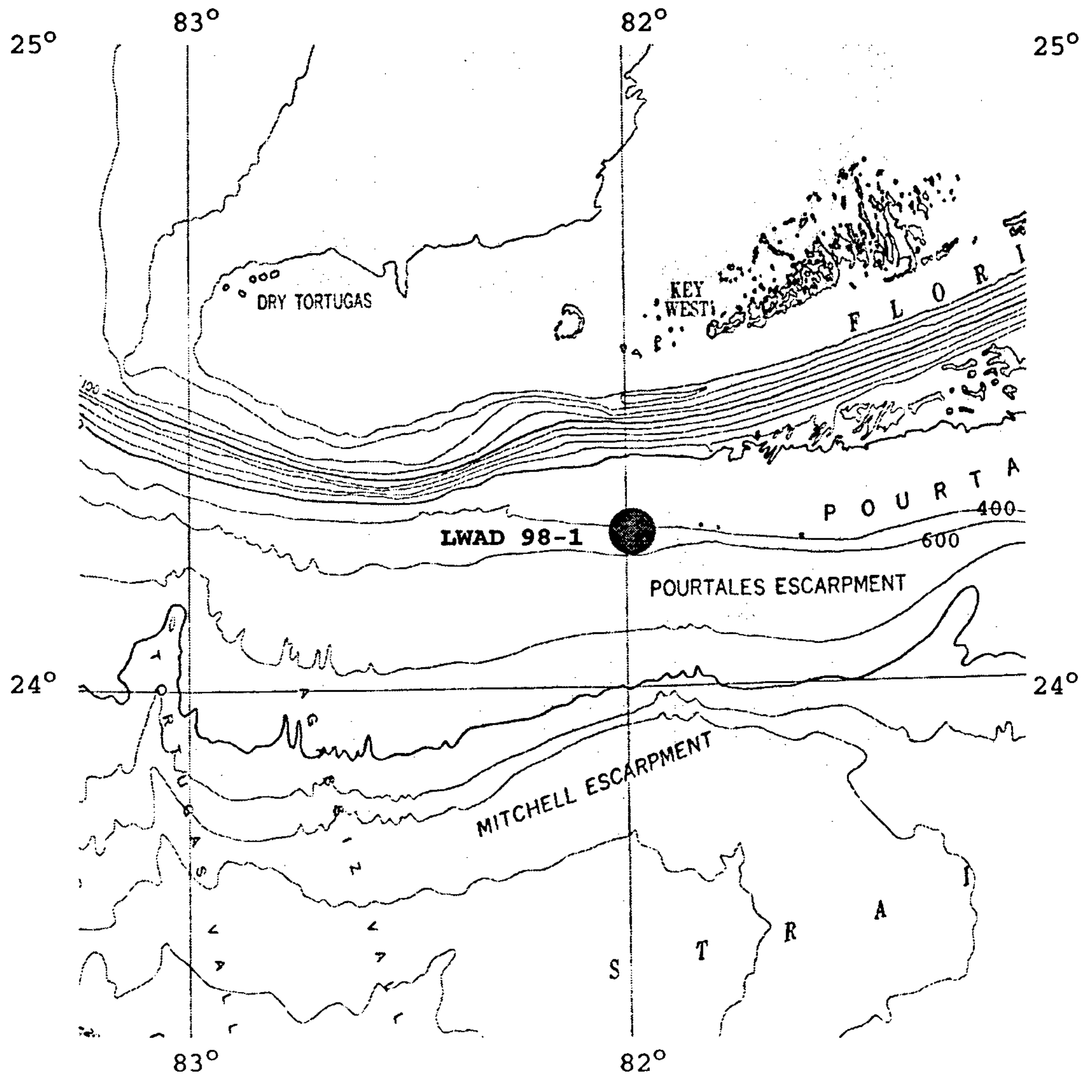


Figure 5: The LWAD 98-1 experiment site. Approximately 34 nmi southwest of Key West, Florida.

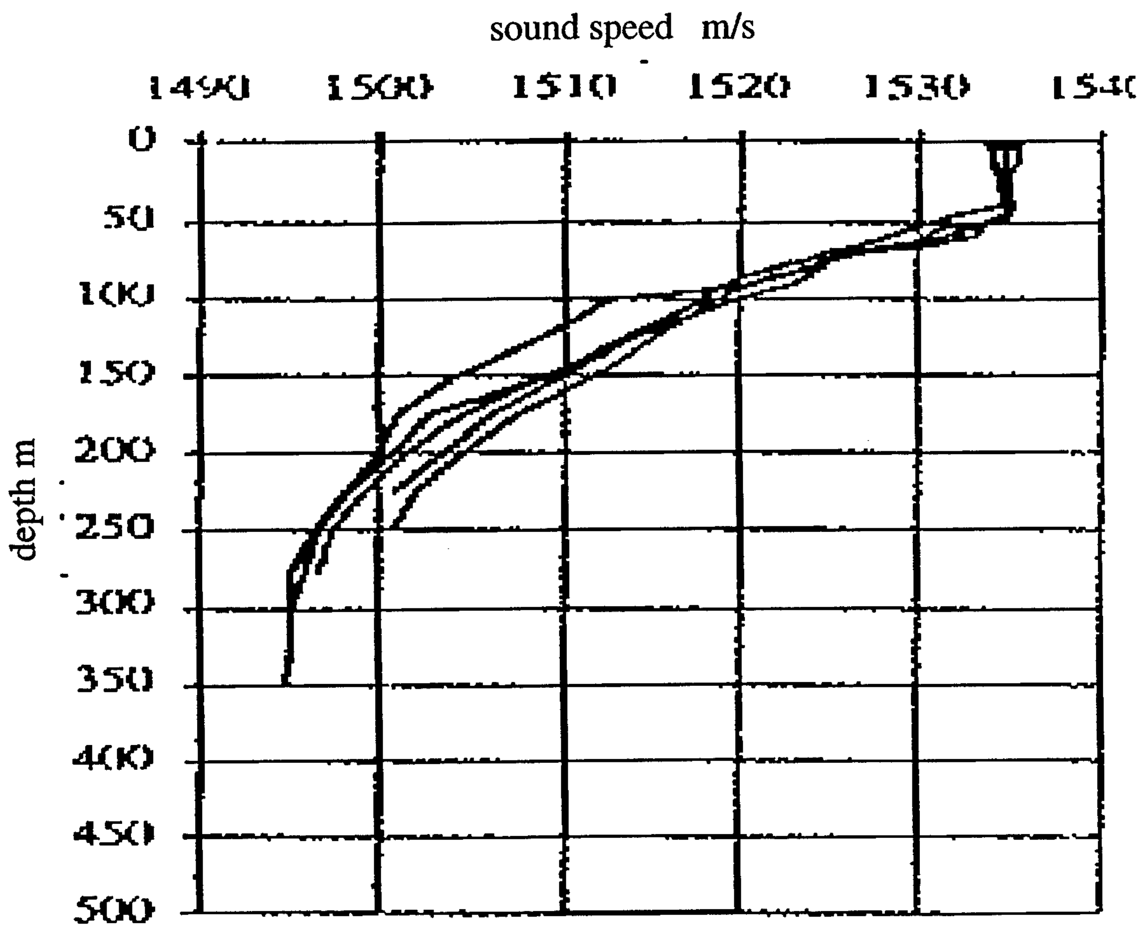
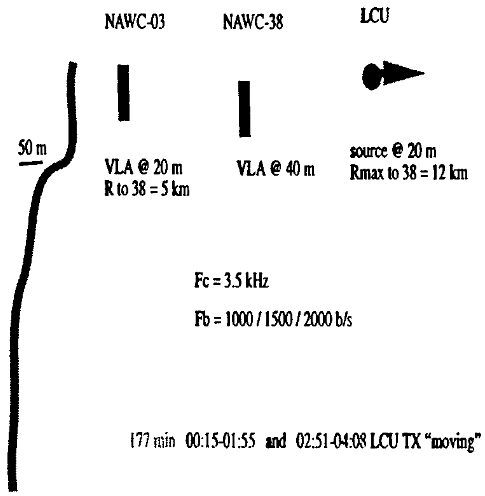
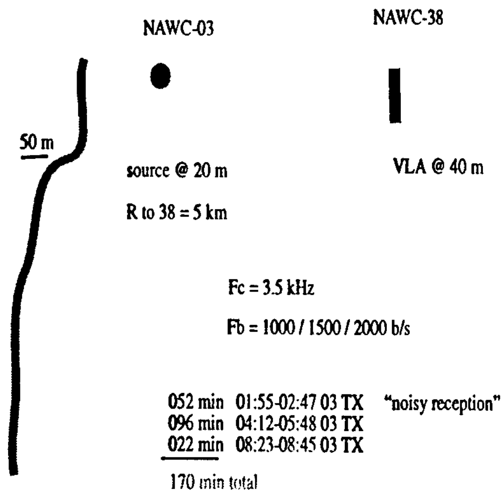
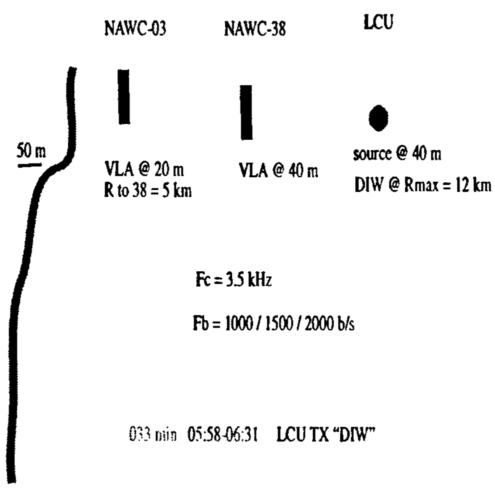


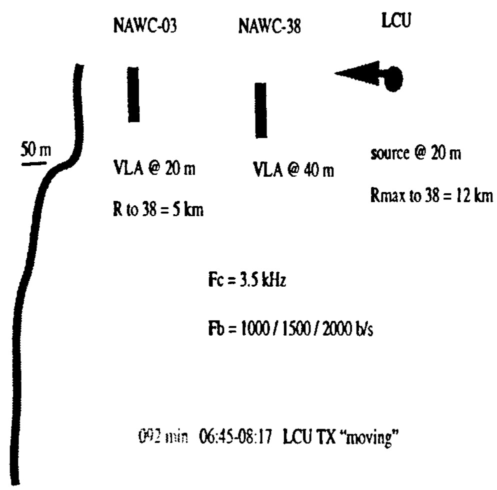
Figure 6: A representative sound speed profile during the LWAD 98-1, CTD taken on board the R/V NAWC 38.

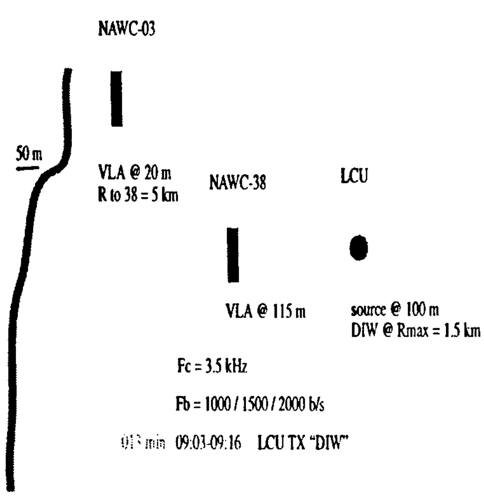
The water column in the OPAREA was 400 meters deep and the mixed layer extended down to 50 meters. Figure 6 shows a typical sound speed profile during the ACOMM exercise. Several VLA/ Source configurations were implemented (VLA and source in the layer, VLA and source below the layer, VLA in the layer and source below the layer, and VLA below the layer and source in the layer). Figure 7 shows the different Source/Receiver configurations.

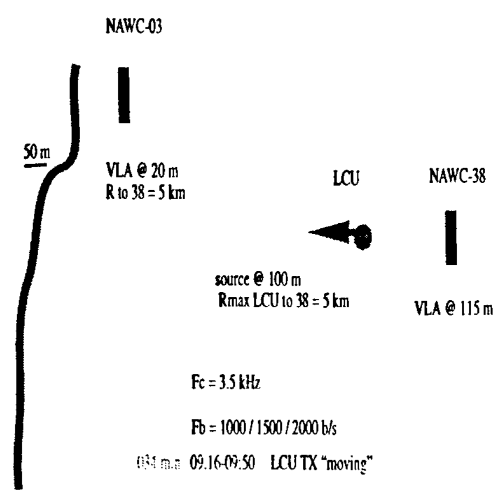

NAWC-03
NAWC-38
LCU
50 m
VLA @ 20 m
R to 38 = 5 km
VLA @ 40 m
source @ 20 m
Rmax to 38 = 12 km
Fc = 3.5 kHz
Fb = 1000 / 1500 / 2000 b/s
177 min 00:15-01:55 and 02:51-04:08 LCU TX "moving"


NAWC-03
NAWC-38
50 m
source @ 20 m
VLA @ 40 m
R to 38 = 5 km
Fc = 3.5 kHz
Fb = 1000 / 1500 / 2000 b/s
052 min 01:55-02:47 03 TX "noisy reception"
096 min 04:12-05:48 03 TX
022 min 08:23-08:45 03 TX
170 min total


NAWC-03
NAWC-38
LCU
50 m
VLA @ 20 m
R to 38 = 5 km
VLA @ 40 m
source @ 40 m
DIW @ Rmax = 12 km
Fc = 3.5 kHz
Fb = 1000 / 1500 / 2000 b/s
033 min 05:58-06:31 LCU TX "DIW"


NAWC-03
NAWC-38
LCU
50 m
VLA @ 20 m
R to 38 = 5 km
VLA @ 40 m
source @ 20 m
Rmax to 38 = 12 km
Fc = 3.5 kHz
Fb = 1000 / 1500 / 2000 b/s
092 min 06:45-08:17 LCU TX "moving"


NAWC-03
50 m
VLA @ 20 m
R to 38 = 5 km
NAWC-38
LCU
VLA @ 115 m
source @ 100 m
DIW @ Rmax = 1.5 km
Fc = 3.5 kHz
Fb = 1000 / 1500 / 2000 b/s
013 min 09:03-09:16 LCU TX "DIW"


NAWC-03
50 m
VLA @ 20 m
R to 38 = 5 km
LCU
NAWC-38
source @ 100 m
Rmax LCU to 38 = 5 km
VLA @ 115 m
Fc = 3.5 kHz
Fb = 1000 / 1500 / 2000 b/s
034 min 09.16-09:50 LCU TX "moving"

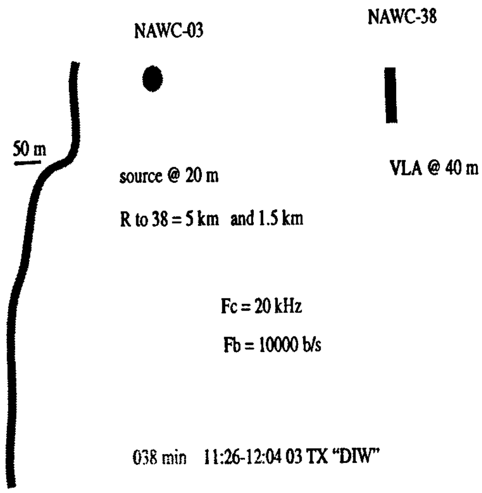


Figure 7: The source/receiver positions during the LWAD 98-1 ACOMM experiment.

3. Projected Waveforms

In both experiments (SCV-97 and LWAD 98-1) prerecorded QPSK modulated pseudo-random sequences were transmitted by the towed mid-frequency sources (BSDS in the SCV-97 and F56 in LWAD 98-1). This mode of operation has proven to be simple and effective.

Three DAT tapes with transmitted signals were generated for the SCV-97 experiment. Each tape had one hour of ACOMM signals which followed a pre-specified structure. Figure 8 shows the signal pattern used which was repeated 172 times to cover one hour of transmission. The three tapes differed in the CW frequency preceding the PRN sequences and by the baud rate of the PRN sequences. The first tape had a CW at 3400 Hz and an ACOMM signal with a baud rate of 1000 b/s; the second tape had a CW at 3500 Hz and an ACOMM signal with a baud rate of 1500 b/s; and the third tape had a CW at 3600 Hz and an ACOMM signal with a baud rate of 2000 b/s. The carrier frequency for the PRN sequences was 3550 Hz. Due to time limitations, the third tape was not transmitted.

For the LWAD 98-1, one tape was generated where the three baud rates (1000 b/s, 1500 b/s and 2000 b/s) were sequentially recorded. The three baud rate PRN signals were preceded by a CW signal at 2500 Hz, at 2700 Hz, and at 2900 Hz. Each CW or PRN was 5 seconds in duration and was followed by 5 seconds of silence. The PRN signals were preceded by a Barker code for synchronization. Between the Barker code and the beginning of the PRN sequences there was a gap (silence) for 0.3 seconds. Figure 9 shows a pattern of the transmitted signal for a single baud rate during the LWAD 98-1. A similar pattern was generated for each of the three baud rates. A complete transmitted sequence (3 baud rates) was 90 second long. This complete waveform was repeated 80 times to cover two hours of transmission by the DAT tape. When the modem on the NAWC 03 was transmitting, it used identical PRN sequences to those described above.

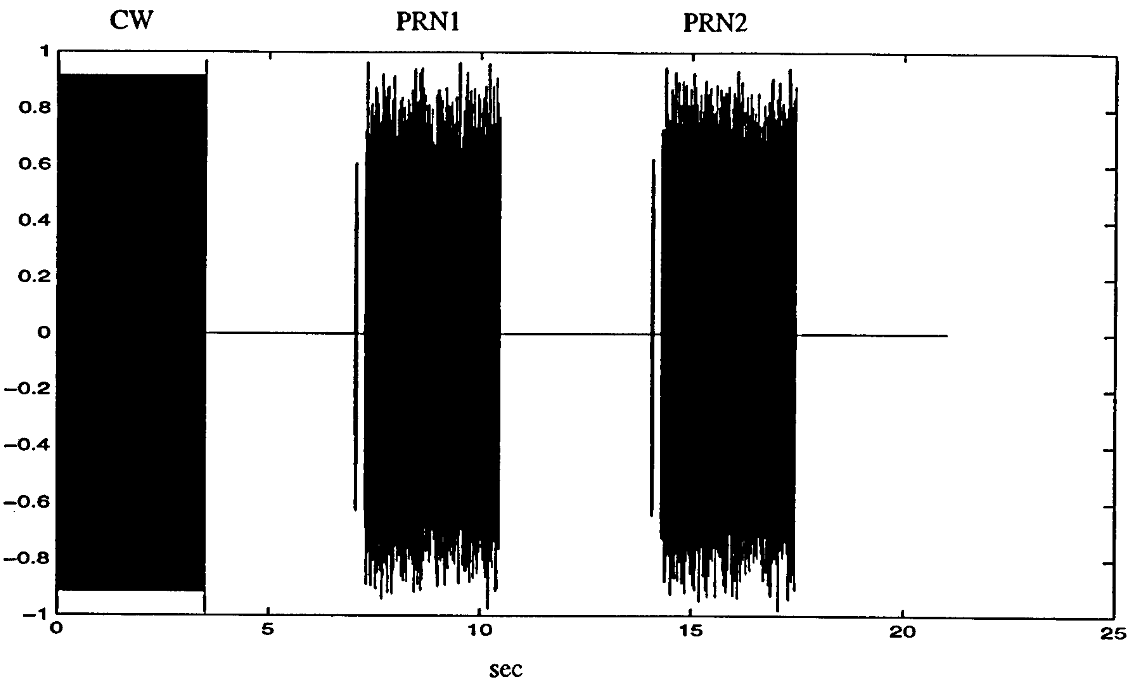


Figure 8: Structure of the transmitted signal during the LWAD SCV-97.

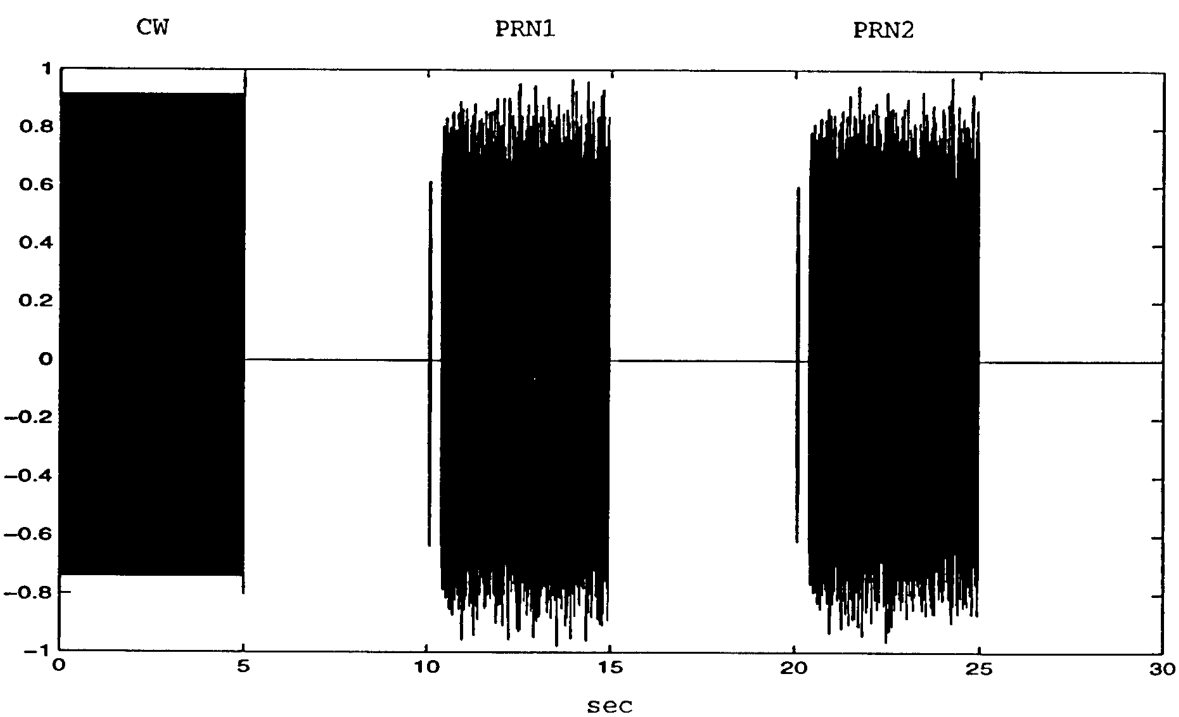


Figure 9: Structure of the transmitted signal during the LWAD 98-1

IV. Received Signals

During the SCV-97 experiment, the ACOMM signal was received and recorded for both segments on the DD Nicholson using the AN/SQS 53-C sonar; the signal was recorded on an Exabyte 8 mm tape using MICRODRAPS software by NUWC. The R/V Gosport and the target recorded the received signal during the first ACOMM segment only. The R/V Gosport received the ACOMM signals using the ACOMM VLA; the signal from the mid-frequency hydrophones was recorded on a DAT 4 mm tape (using an 8 channel Sony DAT recorder) and the 16 channels from the VLA were recorded on a TEAC 8 mm tape (using a 32 channel TEAC recorder). The target recorded the received ACOMM signals on 4 mm DAT tapes using a 2 channel TEAC recorder.

During LWAD 98-1, the ACOMM signals were received on the R/V NAWC 38 and the R/V NAWC 03. Both platforms used identical ACOMM VLA's, see Fig. 10. The raw data on both platforms were recorded on 4 mm DAT tapes using Sony 8 channel recorders. In addition, the raw data on the R/V NAWC 38 was also recorded on an AMPEX DD-2 tape using the ICS data acquisition system and AMPEX DIS-120i recorder. The processed data on the R/V NAWC 38 was stored on 100 MB Zip cartridges using IOMEGA Zip drive connected to the ACOMM modem output. Figure 11 shows the ACOMM lab set up on board the R/V NAWC 38 during the LWAD 98-1.

A summary of the LWAD 98-1 ACOMM experiment logs is presented in Table 2. In general, the received signal on the NAWC 38 showed better than 10 dB SNR when the source/receiver separation was less than 6 km. Figure 12 shows representative plots from the spectrum analyzer output. Figure 13 shows a representative time series of a received ACOMM packet.

As discussed earlier, the environment induced severe distortion to the acoustic signals due to the extended multi-path. A representative impulse response estimation of the acoustic channel is shown in Fig. 14. This impulse response is estimated by convolving a portion of the received signal which contains the received Barker code, Fig. 13, with the inverse conjugate of the transmitted Barker code. This impulse response shows about 10 significant multipaths spreading over 0.3 seconds. A similar analysis was made for the SCV-97 received data.

During LWAD 98-1 ACOMM experiment, an anomalous distortion appeared in the received data, resulting in smeared acoustic signals on the order of 1.5 to 2.0 seconds. Figure 15 shows the spectrogram of a smeared acoustic signal on channel 1. After further investigation, it was determined that the distortion was present only on three channels. Figure 16 shows a time series of the received signal on the 8 channels. Coincidently, channel 1 was used for *in situ* data analysis by the acoustic modem. The cause of this distortion is not known at this time. It might have resulted from cross-talk or interference on the system level (i.e. between the modem processor and the VLA output).

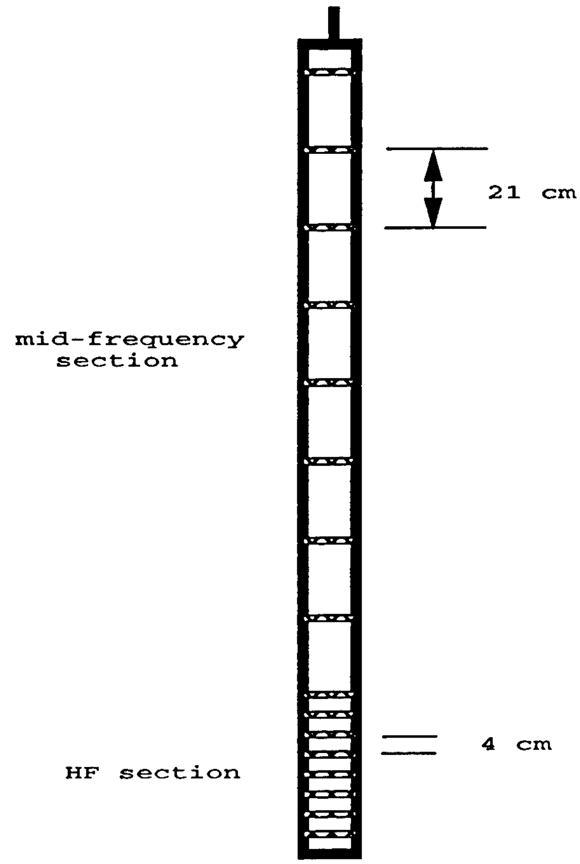


Figure 10: The ACOMM VLA with 16 phones. The bottom 8 phones are spaced for 20 kHz, and the top 8 phones are spaced for 3.5 kHz.

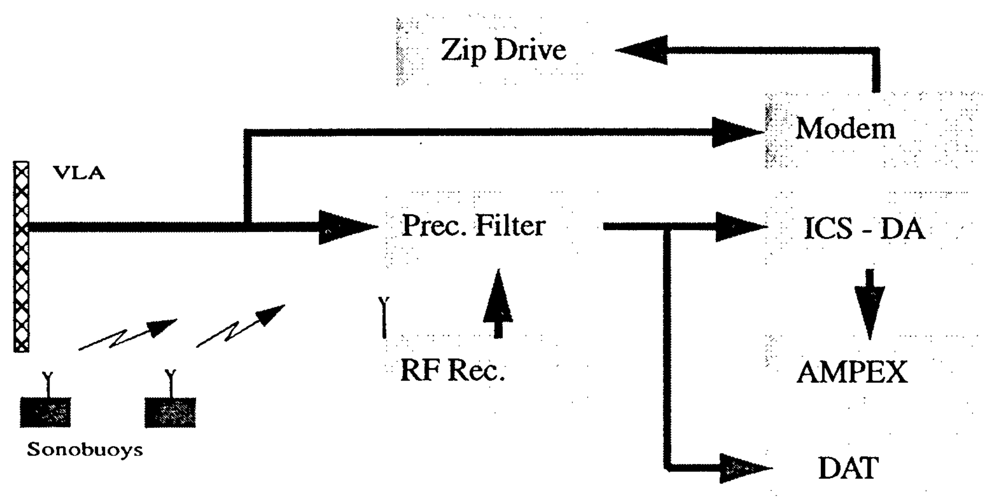
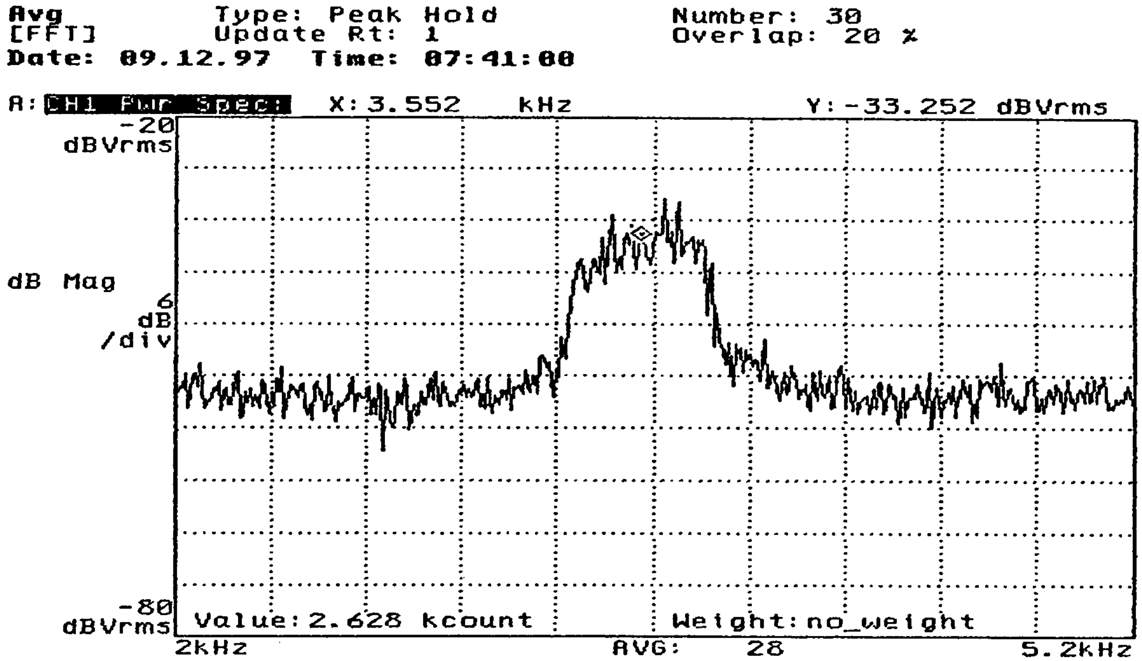


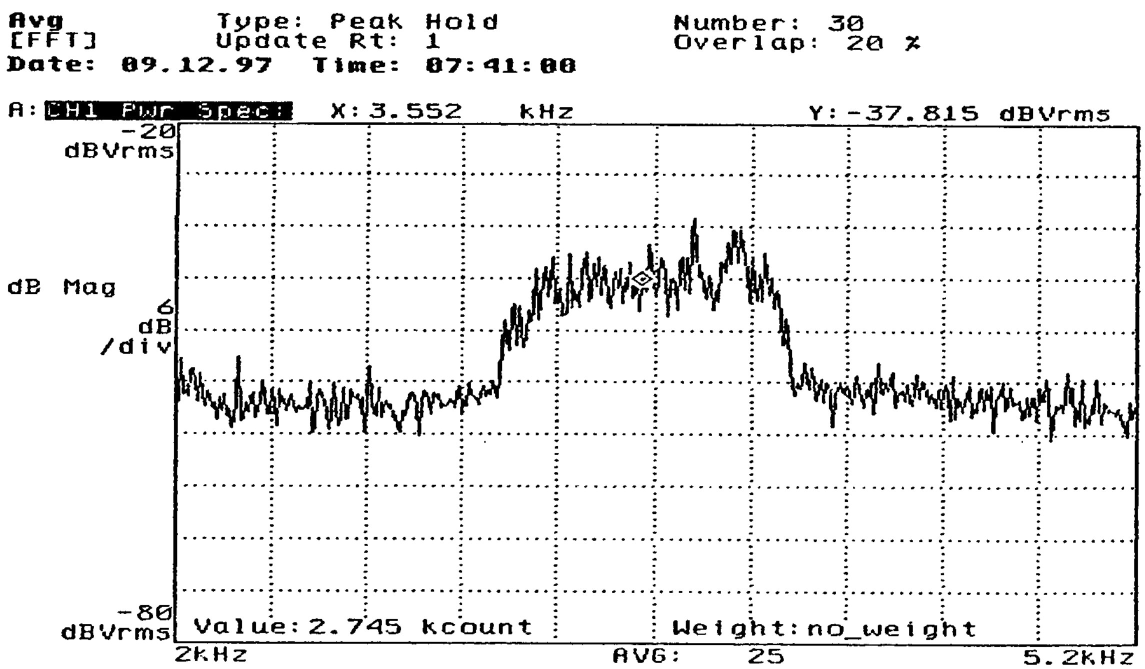
Figure 11: ACOMM Lab on board the R/V NAWC 38 during LWAD 98-1.

Table 2: LWAD 98-1 Event 6 ACOMM COMEX

Experiment	Activity	Comex time (z)	Date	Notes.
Part - 1	LCU moving outbound & TX	00:15:00	12/09/97	
Part - 2	NAWC 03 - DIW & TX	01:55:00	12/09/97	LCU reposition
Part - 3	LCU moving outbound & TX	02:51:00	12/09/97	
Part - 4	NAWC 03 - DIW & TX	04:12:00	12/09/97	noisy reception
	reduce TXgain to 0.3	04:44:00	12/09/97	noise subsided
Part - 5	LCU - DIW & TX	05:58:00	12/09/97	LCU at Rmax
Part - 6	LCU moving inbound	06:45:00	12/09/97	
Part - 7	LCU - DIW "shallow/shallow"	08:01:00	12/09/97	10 s PRN "tape 2"
Part - 8	NAWC 03 - DIW	08:23:00	12/09/97	
Part - 9	LCU - DIW "deep/deep"	09:03:00	12/09/97	10 s PRN "tape 2"
Part - 10	LCU - moving "deep/deep"	09:16:00	12/09/97	09:50:00 LCU signed off
Part - 11	NAWC 03 - DIW & TX	09:30:00	12/09/97	HF --- weak signal reposition
Part - 12	NAWC 03 - DIW	11:26:00	12/09/97	12:04:00 FINEX ACOMM



(a)



(b)

Figure 12: A representative spectrum of the ACOMM received signal during LWAD 98-1. (a) PRN with baud rate of 1000 b/s, (b) PRN with baud rate of 2000 b/s. The plot is from the spectrum analyzer screen.

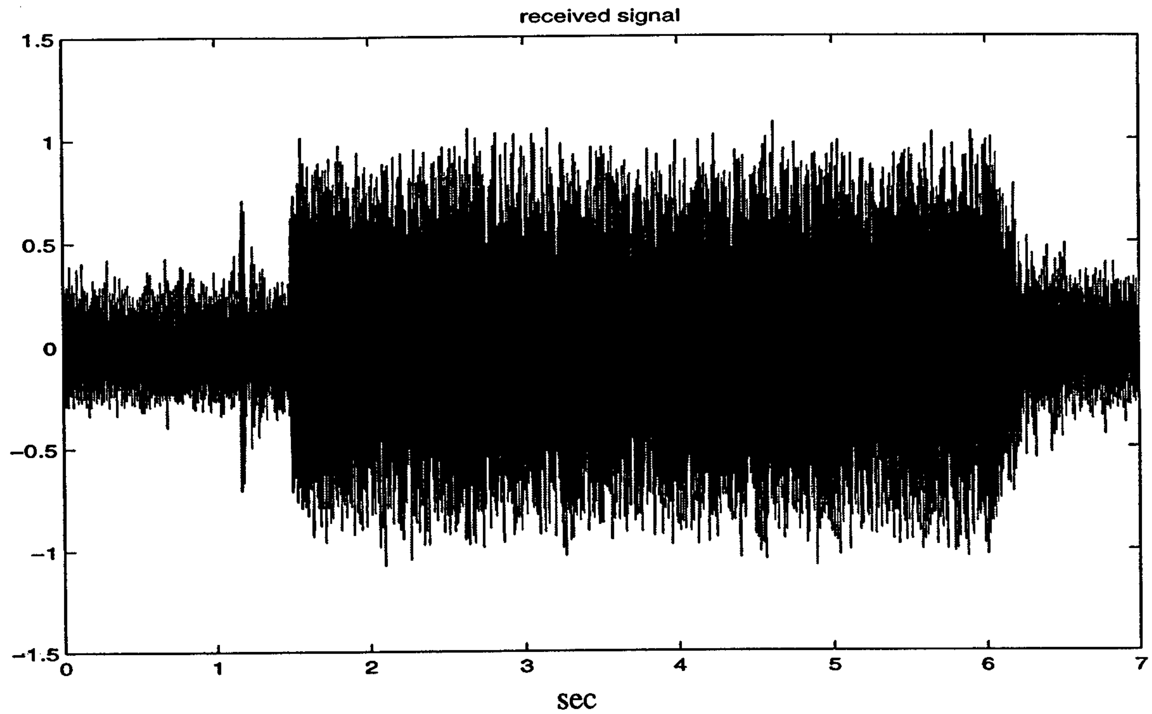


Figure 13: A sample ACOMM received signal during LWAD 98-1.

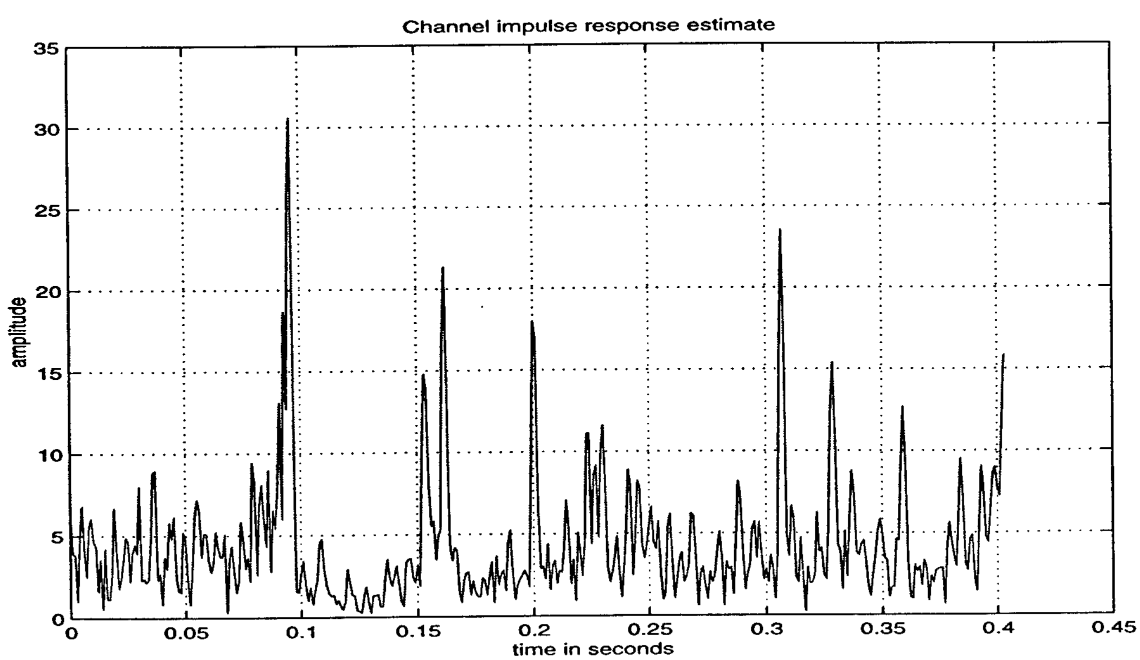


Figure 14: A sample channel impulse response estimation during LWAD 98-1.

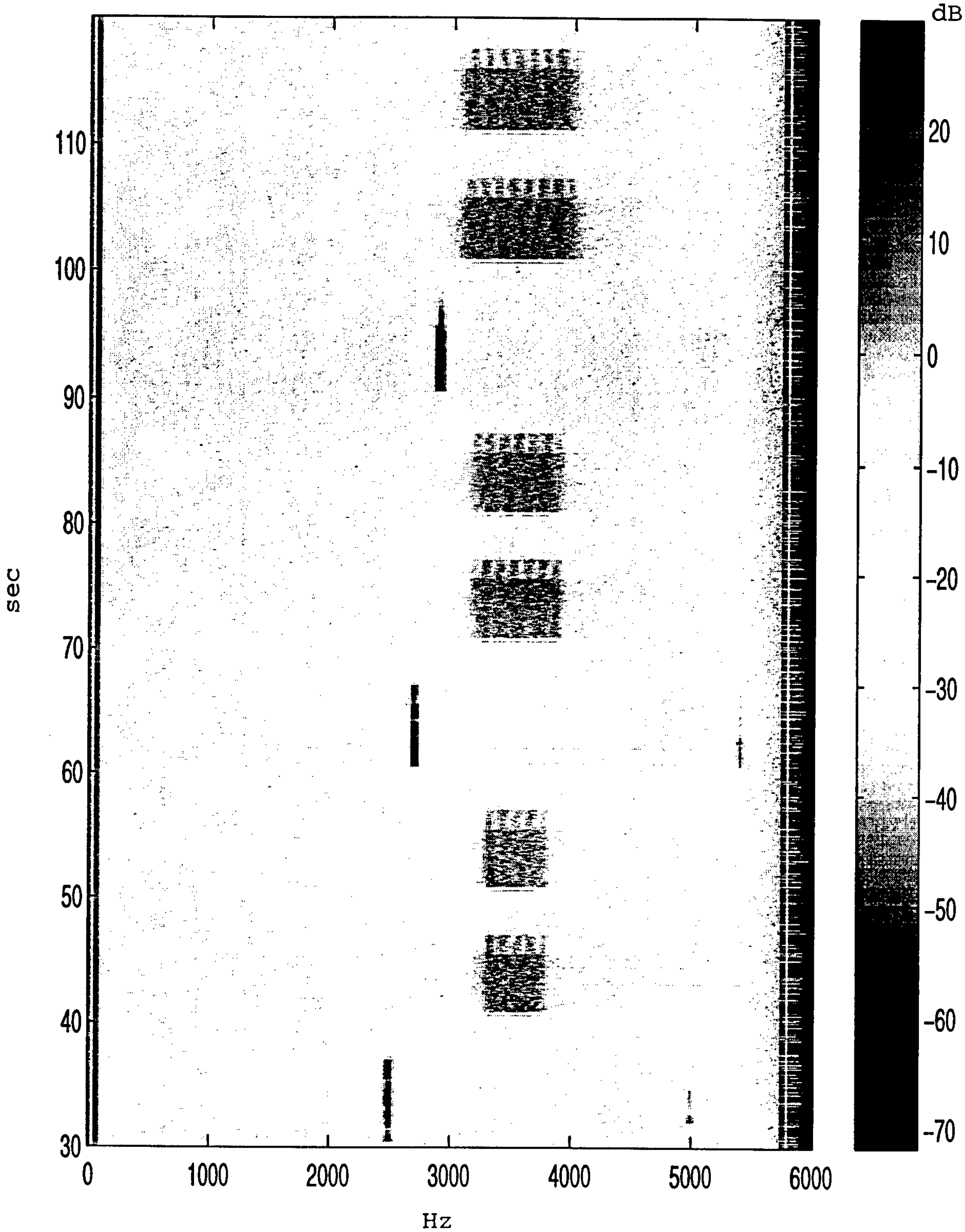


Figure 15: The spectrogram of the received signal during ACOMM LWAD 98-1 on channel 1 from 031030 to 031200 zulu.

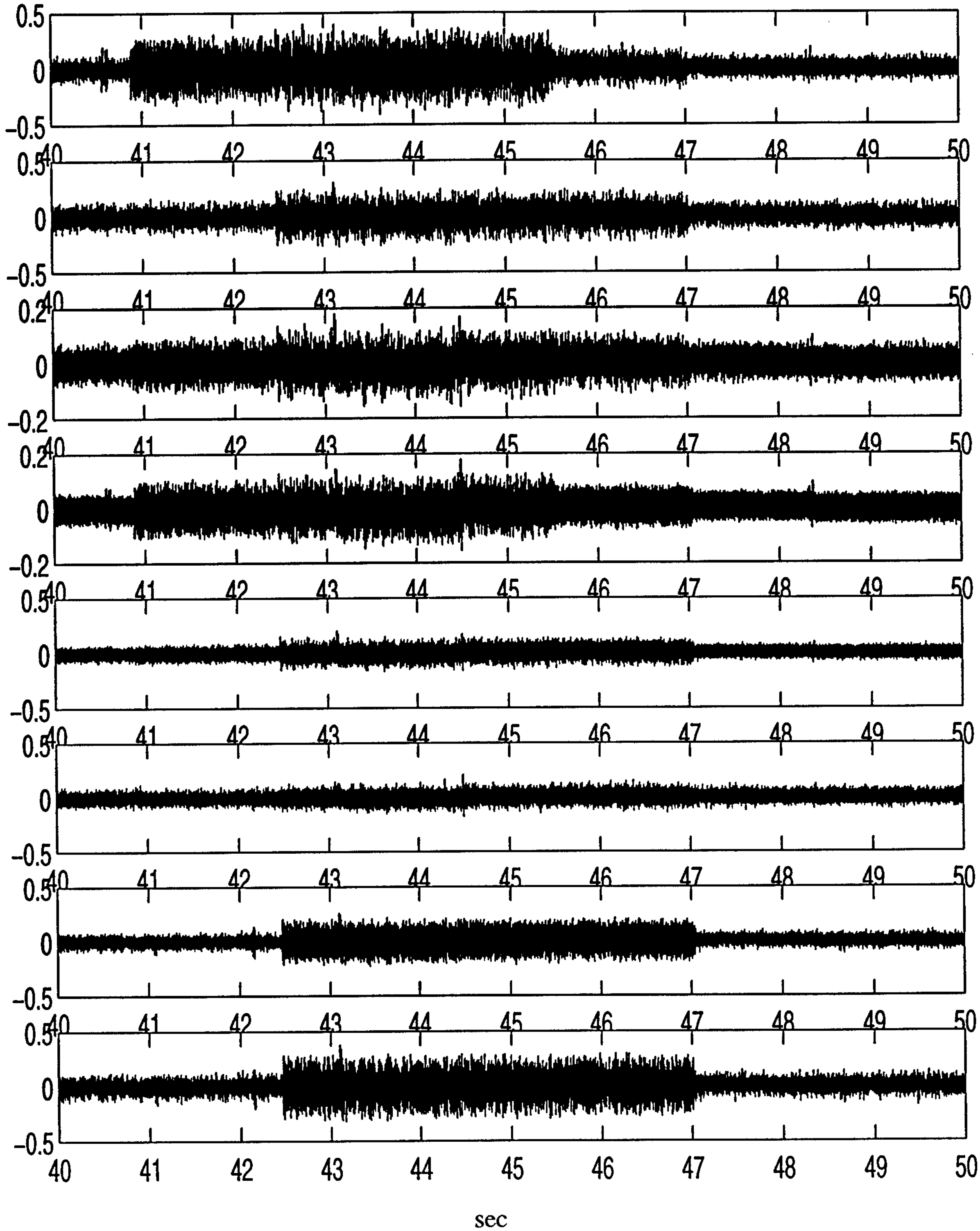


Figure 16: The received signal during ACOMM LWAD 98-1 on channel 1 at 0310 zulu.

V. Real-Time *"In Situ"* Analysis

Real-time *"in situ"* analysis was performed during the LWAD 98-1 on board the R/V NAWC 38. An acoustic modem based on the SHARC digital-signal-processors (DSP) "ADSP-21062" was used for this purpose. The acoustic modem contained a DSP board with 8 SHARC DSPs, but the software (currently installed) was only able to address one DSP. Therefore, we performed the analysis on a single channel due to the limited computational and memory capabilities of the acoustic modem. The improved version of the software (to be used in future experiments) is capable of addressing all 8 SHARC DSPs. Hence, multiple channel data analysis in real-time will be possible.

The data processed by the modem were stored in files on 100 MB Zip cartridges. The IOMEGA Zip drive was attached to the parallel port of the acoustic modem. During the experiment we were able only to conclude the modem status from the activities on the computer screen (i.e. received a signal, triggered, waiting for a signal to trigger, or it is processing a received packet). In future experiments we will have a real-time or semi-real-time plots of the processing results, such as the error distribution, mean-square-error (MSE), phase distortion, and other parameters that might aid in passing a quick and educated judgment on the performance of the modem and adjust the receiver parameters as needed to improve the system performance.

The modem would trigger and start processing a received ACOMM packet if the cross correlation between the transmitted and received Barker code exceeded a certain threshold. The cross correlation result might not exceed the threshold due to a weak received signal as a result of excessive transmission loss along the propagation path, or due to severe distortion induced onto the transmitted signal by the propagation environment.

At any given time during the experiment, the receiver modem aboard the R/V NAWC 38 was set to receive a particular waveform, i.e. either an ACOMM signal with baud rate 1000 b/s, 1500 b/s, or 2000 b/s. The three baud rates were transmitted sequentially with two waveforms at each baud rate (recall the structure of the transmitted signal in Fig. 9). Therefore, the time separation between two pairs of received packets (triggers) at the same baud rate was expected to be 90 seconds. Using this basic calculation, we found that the modem received, triggered, and processed 98% of the transmitted packets when the separation between the source (F56/NAWC-LCU) and the receiver (VLA/NAWC-38) was less than 6 km, see Fig. 17. This ratio dropped down to 50% as the source/receiver separation increased to 12 km. After this range (12 km) the reception and triggering was sporadic. The source level (F56) was maintained at 179 dB based on 2.5 kHz CW signal. Figure 17 group A shows the variation of the SNR as a function of time (in the case of the moving source (LCU) it is a function of range between the source and receiver), Fig. 17 group B shows the error distribution as a function of time (range). The time on the horizontal axis of the figures presents the experiment time in zulu. All the sets in Fig 17 except for set 3 reflect the real-time analysis of the ACOMM data transmitted by the moving source on the R/V NAWC-LCU. Set

3 in Fig 17 reflects the real-time data analysis of the ACOMM data transmitted by the ACOMM modem on board the R/V NAWC 03. The ACOMM modem in the reception mode, was tuned to receive a certain baud rate at a time; i.e. 1000 samples/s, 1500 samples/s, or 2000 samples/s. The gap in the received data in set 1 corresponds to a silence time; the LCU was not transmitting. The SNR for this set was above 10 dB for most of the data and the bit error was less than 0.5%. Set 2 shows an increase in the bit error at the short range and the lack of triggering at long ranges. Set 3 shows that the SNR was approximately 15 dB and the bit error was less than 1% most of the time, except for the time from 05:20 to 05:40 where a broadband noise appeared at the receiver, the source of this noise was determined in the field; we used "txgain =1" assuming that would drive the source at maximum power (180 dB), but we found that would overdrive the source. Maximum power (no broadband noise) was achieved when the "txgain" was set to 0.3. Notice that the SNR fluctuation in set 5, source and receiver are deep, is moderate and the bit error is much larger than that with shallow source and receiver.

Post experiment plotting of the scatter-functions of the processed data show very good clusters in the four quadrants, see Fig. 18. Nonetheless, the MSE plots show that the algorithm did not converge during the training sequence, but rather it formed a "knee" where the MSE dropped down to -15 dB abruptly after the training sequence (500 symbols). The cause of this phenomenon is not known, but we speculate that adjusting the receiver parameters may lead to the elimination of the "knee", and that the algorithm will converge (train) during the training sequence. Quality checking of the received data and receiver parameters adjustment was not possible to perform *in situ* within the allotted time for the ACOMM experiment. On the other hand, if these adjustments were made then the diversity of the collected data would have been very limited.

We plan to re-process the raw data using the modem in the laboratory. This task will be accomplished by playing the raw data from the Sony DAT recorder into the acoustic modem (A/D channels). The obvious advantage of reprocessing the data in the laboratory while adjusting the modem parameters is that there is no need for ship time to repeat the transmission of the acoustic data. Also, with the modified (new version) of the modem software we will be able to process multiple received channels and hence taking advantage of the computational capabilities of the 8 SHARC processors.

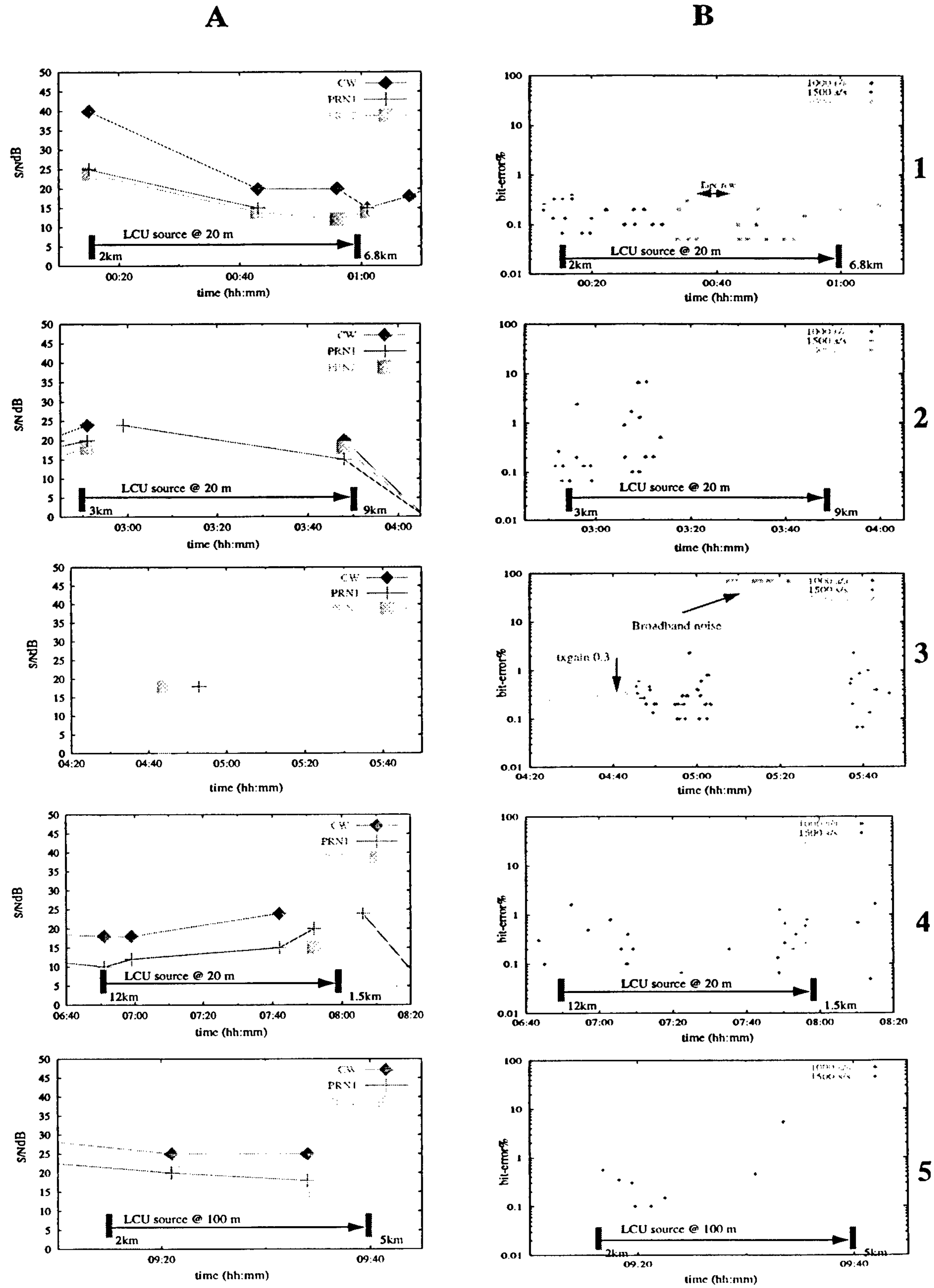


Figure 17: *In-situ* results, (A) SNR (B) bit-error distribution as a function of time (range).

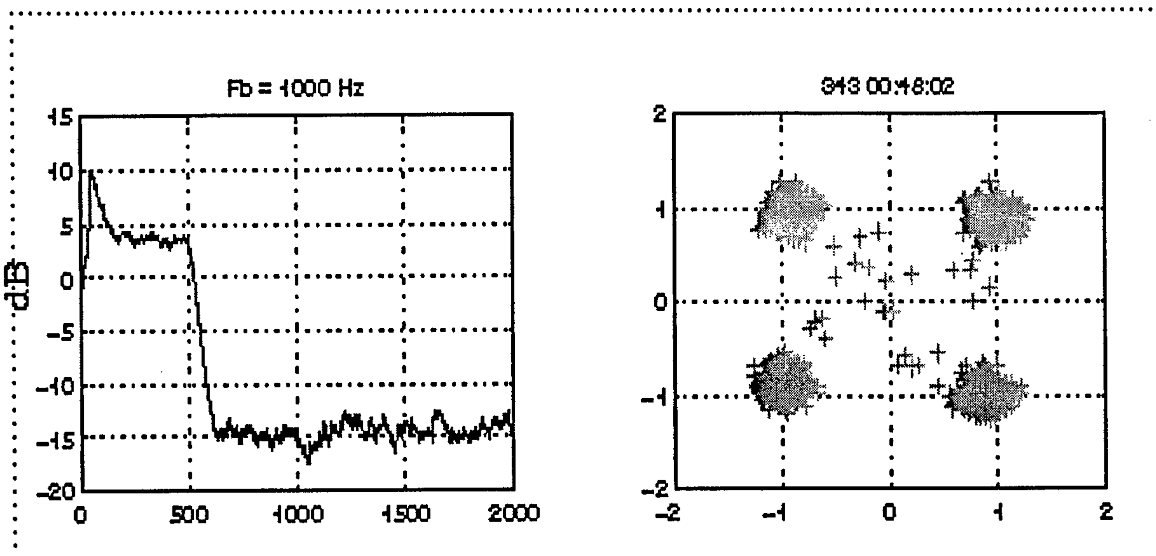


Figure 18: The result of a sample ACOMM packet processed by the ACOMM modem *in-situ*.

SUMMARY AND FUTURE WORK

Phase coherent acoustic communications data were collected during two LWAD experiments. The purpose of the SCV-97 ACOMM experiment was to investigate the communications algorithm work with system beamformed outputs. The purposes of the LWAD 98-1 ACOMM experiment were to examine the acoustic communications performance as a function of range using a moving source, to compare the performance between a moving source and a stationary source, and between receivers at different depths, and finally to examine the at-sea performance of two acoustic modems built by Lockheed - Sanders.

The at-sea data analysis of the Sanders modems were presented in Sec. 5. In general, 98% of data packets were captured by the modem at ranges < 6 km and 50% or less of data packets were captured at longer ranges. The decrease of the trigger rate is believed to be due to the decreased signal-to-noise ratio as range increased.

There are several technical issues which are still being investigated but not yet resolved. These issues will continue to be addressed in the immediate future. There are also acoustic issues relating to the environmental effect on the modem performance which will be addressed in the near future.

A. Technical Issues:

1. The data on channel 1 was contaminated by some kind of feedback between the modem and the

VLA. It showed a superposition of the received signals separated by almost 2 seconds. The data on the other channels seemed clean except for channel 3 and 4 which showed a weaker contamination; the source of this contamination is believed to be due to cross talk from channel 1. As channel 1 is the only channel which was fed to the acoustic modem, it is not clear whether the data received by the modem is affected by the coupling or not, and how the coupling affects the at-sea data analysis. The data analysis needs to be repeated using other channels. For future experiments, the coupling will be eliminated by feeding the data to a (SONY DAT) recorder first. The output of the recorder will be analyzed by the modem.

2. While the modem performance seemed to be self-consistent, the results may be in doubt based on several observations. We have been trying to reproduce the modem results using the Matlab acoustic communications software with only limited success. We found that the symbols grouped nicely into four clusters (a measure of success by most published papers), but the decoded symbols did not agree with the transmitted symbols.

3. We have not been successful in equalizing the at-sea data using the conventional Matlab communication software. It is an on going effort. We are trying different parameters in the equalizer and also trying the sparse equalizer. It is fair to conclude that phase coherent communications is not an automatic scheme yet.

4. Initial attempts to analyze the data using conventional acoustic communication software did not yield positive results. The data will be re-visited after the above issues are resolved.

B. Acoustic Issues:

1. Almost 15 hours of acoustic transmission data were collected form the LWAD 98-1 and SCV-97 ACOMM experiments. This presents a rich data set to study the temporal and spatial (range) variations of the channel impulse response. The channel impulse responses will be analyzed statistically on one hand and analyzed individually on the other hand to see how it affects the sparse equalizer performance.

2. Signal fluctuation statistics will be studied for a single phone versus a single beam pointing to the source. It is believed that beam fluctuations are less than the single phone and may aid in signal equalization. Beam signal-to-noise ratio may also improve the communication performance to a longer range than the single phone or multiple phones equalized incoherently.

3. The data will be tested with the performance prediction model [8] which requires a fair understanding of the acoustic channel fluctuations.

ACKNOWLEDGMENT

This work is supported by the Office of Naval Research. We greatly appreciate the participation in

the Littoral Warfare Advanced Development program.

REFERENCES

1. D. Kaiser et al., "Joint Naval Sea Systems Command and Littoral Warfare Advanced Development (LWAD) System Concept Validation (SCV-97) Test Plan", Marine Acoustics, Inc., Sept. 1997.

2. Multiple Authors, "Joint Naval Sea Systems Command and Littoral Warfare Advanced Development (LWAD) System Concept Validation (SCV-97) Quick Look Briefing Proceedings", Marine Acoustics, Inc., 28 October 1997.

3. Paul J. Bucca, James K. Fulford, and Redwood W. Nero, "Pre-Experiment Environmental Characterization for the Joint NAVSEA/Littoral Warfare Advanced Development System Concept Validation (SCV-97) Tests in Long Bay, SC", NRL Memorandum Report NRL/MR/7182-97-8057, 29 August 1997.

4. Raymond J. Soukup and Peter M. Odgen, "Bottom Backscattering Measured Off the South Carolina Coast During Littoral Warfare Advanced Development Focused Technology Experiment 96-2", NRL Memorandum Report NRL/MR/7140-97-7905, 28 April 1997.

5. George A. Kerr, Paul. J. Bucca, James K. Fulford, and Stephen W. Snyder, "Environmental Variability During the Littoral Warfare Advanced Development Sponsored Focused Technology Experiment (FTE 96-2)", NRL Memorandum Report NRL/MR/7182-97-8056, 8 August 1997.

6. Lee Shores et al., "Littoral Warfare Advanced Development (LWAD) LWAD 98-1 Experiment, Test Plan", Marine Acoustics, Inc., December 1997.

7. Multiple Authors, "Littoral Warfare Advanced Development (LWAD) LWAD 98-1 Quicklook Briefing Proceedings", Marine Acoustics, Inc., 22 January 1998.

8. T.C. Yang, and A. Al-Kurd, "Environmental Impact on Phase Coherent Underwater Acoustic Communications: A Physics Based Approach", in press.